Copy No. 35

NASA Program Apollo Working Paper No. 1110

AN ANALOG SIMULATION STUDY OF THE TETHER CONCEPT OF APOLLO DOCKING CONTROL

DISTRIBUTION AND REFERENCING

This paper is not suitable for general distribution or referencing. It may be referenced only in other working correspondence and documents by participating organizations.

NASA

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
Houston, Texas

April 15, 1964

NASA PROGRAM APOLLO WORKING PAPER NO. 1110

AN ANALOG SIMULATION STUDY OF THE TETHER CONCEPT OF APOLLO DOCKING CONTROL

Prepared by: Thomas E. Moore

Thomas E. Moore
AST, Systems Analysis Branch

Clarke T. Hackler

Clarke T. Hackler
AST, Systems Analysis Branch

AUTHORIZED FOR DISTRIBUTION:

Warren Gillespie, Jr.

for Maxime A. Faget
Assistant Director for Engineering and Development

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

April 15, 1964

AVAILABLE TO NASA HEADQUARTERS ONLY

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

AN ANALOG SIMULATION STUDY OF THE TETHER CONCEPT OF APOLLO DOCKING CONTROL

SUMMARY

A piloted simulation has been conducted in which the relative advantages of the tether concept of spacecraft docking and direct docking of spacecraft have been evaluated. Both the Apollo transposition and lunar orbit dockings have been investigated.

This study investigated the effect of cable reel-in rate, cable tension, and attitude control system mode upon the tether docking. The effect of attitude control system mode was evaluated for the direct docking concept.

The results of this study revealed that the control problems and contact conditions were very nearly identical for both docking concepts. Based on the study findings, it is concluded that there is no apparent advantage of the tether concept over the direct docking concept.

INTRODUCTION

The Apollo Lunar Landing Mission includes two docking maneuvers: one occurs shortly after translunar injection when the C/SM detaches from the S-IVB and docks with the LEM/S-IVB, and the other occurs following lunar orbit rendezvous when the LEM docks with the C/SM. The accuracy with which these maneuvers can be performed is dependent on the characteristics of the spacecraft control system and the adequacy of the displays and visual cues available to the pilot to execute the maneuver. The contact conditions obtained determines the limits to which the docking-latching interface must be designed.

Earlier studies of the docking control problem (refs. 1 to 4) assumed that the maneuver would bring the vehicles into direct contact and investigated the accuracy with which this could be accomplished using varied modes of attitude control. A more recent concept has evolved in which the two vehicles are tethered while still a few feet apart and then reeled together to complete the docking maneuver. The objective of this newer concept is to obtain more precisely controlled contact conditions that will alleviate the weight problem of docking fixture hardware design.

Since the relative advantage of tethered versus direct docking had not been clearly established, an analog simulation study was conducted by the Guidance and Control Division to investigate tethered docking and to compare the docking results (for example, contact velocities and displacements, fuel expended) of the two methods. It is the purpose of this report to present and discuss results of this study.

SYMBOLS

ρ Angle between docking axes of two spacecraft

σ Standard deviation about mean or average

ϕ Relative roll angle error between two docking spacecraft

DESCRIPTION OF SIMULATION

The docking simulation was implemented by coupling an analog computer solution of the two six-degrees-of-freedom dynamical equations of relative motion of the Apollo Command/Service Module and the LEM or the LEM/S-IVB with a simulated cockpit. The cockpit represented the C/SM for transposition docking and the LEM for lunar orbit docking. The equations included a simplified representation of the dynamics of a cable and reel control used to draw the vehicles together for the tethering maneuver.

Displays and Controls

Cockpit displays.- The cockpit information displays are shown on figure 2. From left to right the instruments used consisted of a cable length meter, distance between connector points meter, three-axis eight ball attitude indicator, roll-angle meter, roll angle (of the other vehicle) meter, cable-velocity meter, cable-tension meter, and a two-beam cathode ray oscilloscope. One beam of the oscilloscope, which was presented as a circle, represented the azimuth and elevation angle to the other vehicle. The other beam, which was presented as a dot, was a function of the azimuth and elevation angles from the second vehicle. The function of these angles was such that if the attitudes of the two vehicles were alined for docking, the dot and circle were concentric. Coincidence of the dot and circle when displaced from the center of the scope represented proper attitude alinement in pitch and yaw, but indicated a vehicle misalinement in the YZ plane. Roll attitude error could not be determined from the scope; therefore, the roll attitude of the other vehicle was displayed on a meter.

Cable control.- A two-speed reel-drive motor was assumed which had a peripheral reel speed or cable speed of 1.8 or 3.0 in./sec. A clutch was assumed between the reel drive and reel which was set to slip at a preset tension. This maximum tension was adjustable at the computer from 1 to 250 pounds and could not be changed by the pilot. The spring characteristics of the cable were varied so that the maximum tension occurred at 1 inch of cable stretch. One inch was the minimum stretch that could be used for maximum tension without encountering computer noise problems. The pilot could engage or disengage the clutch with the button switch indicated on the left of figure 2. The cockpit throttle was used to command reel drive speed. This throttle is adjustable, but for the simulation only the two indicated positions of 1.8 and 3.0 in./sec were used. A block diagram of the cable control is shown in figure 1.

Attitude control.- Each vehicle was capable of one of three modes; rate command attitude hold (deadband = .5°), rate command, or open loop jets on or off (no minimum impulse capability). For the C/SM, an on-off system with deadband and hysteresis was used. The hysteresis was fixed at .05° and the rate feedback gains for attitude hold were adjusted to give a limit cycle velocity of .025°/sec. For the LEM or LEM/S-IVB, a pseudo rate on-off logic was used. The minimum pulse width of the PRL was adjusted for 8 msec to provide proper limit cycle for the LEM. The limit cycle pulses of the S-IVB are about 80 msec; therefore, the S-IVB accelerations used in the simulation were increased by 10 to provide the proper limit cycle velocity. Attitude control was afforded by a 3-axis pencil controller located between the pilot's knees.

Translation control.- A 3-axis T-handle controller was located between the pilot's knees. No minimum impulse capability was provided.

TEST PROGRAM

The docking maneuver was performed direct (without cable) and tethered. The tethering device was assumed pivoted at each connection point, and for the majority of runs it was assumed to be a cable capable of tension only. The attitude control system was flown in each of three modes as previously noted. Cable tensions of 1, 5, 10, 20, and 100 pounds were investigated during the transposition dockings and tensions of 1, 10, 100, and 250 pounds in the lunar orbit docking. The majority of runs was initiated with the 20-foot cable already connected and with all relative velocities zero, except for limit cycle angular velocities. The attitudes were misalined 10 degrees/axis, and the cable or line of sight between connectors was at 10 degrees with respect to the major docking axis (X-axis) of the unpiloted vehicle. The docking technique used was to first reduce the angular errors, aline the docking axes, and then reel (translate for direct docking) the two vehicles together. A total of 173 runs was made during the simulation.

Tether Transposition Docking

Cable connect.- In addition to the above procedures, the tether cable was connected to the LEM/S-IVB using a rigid boom. The C/SM, with a rigid 20-foot boom extending from the docking connection point, was separated from the S-IVB and rotated 180 degrees. The end of the boom was then connected to the S-IVB.

Determination of technique.- With the cable already connected, initial conditions for larger misalinements were used to determine the tethered docking technique. The cable was at 60 degrees with respect to the S-IVB docking axis, and at 90 degrees with respect to the C/SM docking axis. The techniques investigated were:

(1) The attitude of the C/SM with respect to the S-IVB was alined, and the (Y-Z) thrusters were then used to aline the docking axis. The two spacecraft were then reeled together. Alinement of docking axes was maintained with the (Y-Z) thrusters.

(2) The C/SM was reeled in after the attitude with respect to S-IVB was alined. At about 40 inches displacement, the clutch was disengaged and the docking axes were alined with the (Y-Z) thrusters.

(3) The docking axis of the C/SM was alined along the cable and then reeled in. At about 40 inches, a coordinated translation and rotation maneuver was performed to aline attitudes and docking axes.

Compression.- Several runs were performed with the tethering device being capable of tension and compression. The coefficient of compression used was equal to the coefficient of tension, such as 1 lb/in. or 100 lb/in. The pilot task during these runs was to prevent buckling due to boom compression.

S-IVB stabilization failure.- Capability of docking to the S-IVB without stabilization was investigated for angular velocities of the S-IVB of .025, .25, 1.0, and 2.0 deg/sec.

Tether Lunar Orbit Docking

Tension greater than translation thrust.- A cable tension of 250 pounds for tethered docking, which is 50 pounds higher than the translational thrust, was investigated. This enabled the pilot to maintain continuous tension and still be pulled in by the cable.

Center of gravity offsets.- Center of gravity offsets of up to 10 inches were investigated for the open loop attitude control mode. The following attitude acceleration due to translation thrusting was used:

T_x $.47°/\text{sec}^2/\text{inch}$ in pitch

T_z $.47°/\text{sec}^2/\text{inch}$ in pitch

T_y $.72°/\text{sec}^2/\text{inch}$ in roll

Direct Docking

Except for the cable reel-in procedures, the direct docking tests were identical to the tether docking tests for both transposition and lunar orbit investigations.

DISCUSSION OF TEST RESULTS

For clarity of presentation, the ensuing discussion has been divided into sections on transposition and lunar orbit docking. In addition to the presentation and discussion of numerical data, some comments are made relative to control problems associated with tether docking. The pilot displays used in this simulation are discussed and compared with the displays and visual cues available to the pilot during actual docking maneuvers.

Transposition Docking

Effect of control system.- The transposition docking maneuver was performed without difficulty in either the direct or tether mode. The type of control system had some effect on terminal conditions, although the effect was not pronounced. The primary difference existing among the different control modes was that the pilots had a more difficult time effecting the maneuver in the open loop mode. Both the displacement and velocity errors were larger in the open loop control mode than in the rate command-attitude hold mode for both direct and tether docking. However, it is interesting to note that in the open loop control mode, the displacement velocity errors during direct docking were smaller than those obtained during the tether docking. The same is also true of the attitude errors ϕ and ρ and to a large extent in fuel consumption. The probable reason for this is that the pilots were required to monitor the cable during the tether docking which complicated the control task. The terminal conditions obtained using the rate command-attitude hold control mode were essentially the same for the direct or tether docking.

Effect of cable tension.- Cable tension was varied from a minimum of 1 pound to a maximum of 100 pounds. Inspection of the data of table 1 shows very little correlation between cable tension and terminal conditions for most of the tensions investigated.

Cable connect.- The complete docking maneuver, that is, separation of the C/SM from the S-IVB and 180° turnaround, was performed without difficulty. Both the attitude and translational fuel expenditure increased, but the attitude and contact velocities and displacements at boom contact were about the same as the values obtained for direct docking.

Docking technique for large initial errors.- Of the several docking techniques investigated for large initial errors, the most effective technique was to reduce the attitude errors, then aline the docking axes, and reel in. Thus, the procedure was identical to that used for small angular displacement once the initial attitude errors were reduced to near zero. The other two techniques investigated required excessive attitude and translational fuel expenditure to complete the docking maneuver. Terminal conditions at contact were about the same for all procedures investigated.

S-IVB stabilization failure.- Docking in either the direct or tether mode was possible with S-IVB control system failures providing the angular rates of the S-IVB did not exceed 1 deg/sec. With rates greater than 1 deg/sec, the translational capability of the C/SM was not sufficient to maintain contact with S-IVB long enough to complete the docking maneuver.

Lunar Orbit Docking

Effect of control mode.- As in the case of transposition docking, the lunar orbit docking was effected without undue piloting problems. The control system mode influenced terminal conditions due to the light configuration of the LEM (low mass, inertias). Displacement errors, as shown in table 2, were larger in the open loop mode than in the rate command-attitude hold mode for both the direct and tether docking maneuver. However, except for a 250-pound cable tension, the magnitudes do not appear to be significant. The contact velocities are generally independent of docking method or control mode except at the 250-pound tension. Contact velocities at this cable tension were about 4.8 times greater in the open loop mode as in the rate command-attitude hold mode (8.5 to 1.75 in./sec). The reason for this is that when the LEM was in the open loop mode, the interaction of the cable and translational thrusters caused the two connector points to start a circular oscillation about 6 inches before contact. The angular rates were so high that the centrifugal force equaled the centripetal force of the cable. Hence, to make contact, the pilot was forced to release the translational thrusters and the high tension snapped the two vehicles together which caused contact velocities of between 8 and 10 in./sec. The oscillations were also responsible for the increased attitude fuel expenditure. Attitude errors were larger in the open loop mode than the rate command-attitude hold mode, but since the largest attitude error was around 3.9 degrees, this does not appear to be a critical item. Attitude fuel consumption was about the same for the rate command-attitude hold in both the direct and tethered dockings for tensions below 100 pounds, but was significantly higher for the open loop control mode. For a tension of 250 pounds, the LEM attitude fuel consumption was nine times greater and the C/SM attitude fuel consumption some twelve times greater in the open loop than the rate command-attitude hold mode. The LEM translational fuel at the 250-pound tension was also greater (25.5 to 14.7 pounds) in the open loop mode than the rate command-attitude hold mode.

Effect of cable tension.- Variation of the cable tensions from 1 pound to 100 pounds did not affect terminal conditions or fuel consumption. For a cable tension of 250 pounds, contact velocities and attitude and translational fuel consumption increased. The increased magnitudes of these variables were due to the technique used in performing the docking maneuver. The technique used was to thrust against the cable tension to prevent cable slack. Just prior to contact the translational thrusters were deactivated and the cable allowed to draw the two vehicles together. The technique was satisfactory for the rate command-attitude hold mode, but not for the open loop attitude control mode for the reason stated above.

Center of gravity changes.- The center-of-gravity offsets of 10 inches caused no change in contact conditions. This was because the angular rates caused by the translational thrusters were small (0.5 deg/sec) compared to the minimum angular velocities (2 deg/sec) commanded by the pilot.

Control Problems in Tethered Docking

One of the piloting problems in flying the tethered docking simulation was in keeping the cable taut at contact. In about 25 percent of the runs, the cable had from 1 to 4 inches of slack present at contact. Because the entire task requires quite precise control just prior to contact, the presence of the cable effectively constituted another degree-of-freedom to be controlled. The problem can be minimized by using either extremely small tensions, or it can be eliminated by using cable tensions greater than the vehicle translational thrust capability.

Small tensions alleviate the slack since the force drawing the two vehicles together is small enough to prevent large relative velocities building up in small time intervals. For intermediate tensions, the relative velocity builds up quickly and the cable goes slack rapidly due to the low cable reel-in rate. A high cable reel-in rate would either alleviate or eliminate cable slack, but at the expense of higher contact velocities. Large cable tensions eliminate the problem of a slack cable since the pilot uses the translational thrusters as a controlling brake. However, the use of thrusters in this manner causes both the translational and attitude fuel expenditure to increase significantly.

The use of a tethering device that has the capability of both tension and compression presents a possible piloting problem. If the device has these properties, the pilot will be required to prevent sustained oscillations in relative distance between the two vehicles from building up. This possibility exists because in tension the two vehicles are drawn together while in compression they are forced apart. Because the damping is almost zero, the system is very nearly neutrally stable. If the pilot is not careful in applying translational thrust, the oscillations can be sustained and perhaps diverge rather than converge. This is a serious problem at near contact distance since under these conditions it is possible for the velocity to be so high as to cause structural damage at contact.

Pilot Displays

The displays used by the pilot in this simulation probably gave more precise information than will be available in the real situation. This is partially due to the limited discriminatory capability of the pilot and partially due to visibility limitations just prior to contact. Some of the information (for example, attitude, cable rate, tension) may be identical to that used in the simulation. The quantities in question are relative vehicle closure rate, exact positions of the docking fixture, and the difference between separation distance and actual cable length to be reeled in.

At least two of the variables, lateral and vertical separation of the two docking fixtures, can be obtained in the real situation by using a simple sighting device of some type. The horizontal separation distance is difficult to obtain without some degree of complexity. A probe type device could provide the information for the last six inches of the maneuver, but would impose a weight and design penalty to the vehicle carrying the sensor. However, the pilot may be able to determine the horizontal separation distance well enough to perform the maneuver with position errors no greater than those obtained in this study. It is very likely that the actual docking fixture will be able to accommodate larger position errors than those determined in this study. In that event, a sensor to detect horizontal separation will probably be unnecessary. The pilot may also be capable of detecting relative velocities between vehicles well enough to preclude the use of a sensor to obtain this quantity.

CONCLUDING REMARKS

The present study has indicated that while the tether-concept of docking control is feasible, there is no significant advantage to this mode over the direct docking concept in terms of contact accuracy, contact velocities, and fuel expenditure. The additional weight and power requirements of the tether concept of docking were not considered in this study. These results are conditioned by the finely resolved docking situation display afforded the pilots of the simulation study. It is believed, however, that regardless of the concept of docking that is employed, the pilot of the active spacecraft must be provided with visual aids that will give a comparable quality of information. The area of visual docking aids has not been fully explored; however, previous preliminary tests at NAA Columbus (ref. 1) have shown the usefulness of very simple devices.

The present study also showed that the role of the pilot in control of the docking maneuver is not significantly different during a tethered docking maneuver than during a direct docking maneuver.

The dynamics of the reel and cable assumed for the present study were quite simple, but appear realistic from the standpoint of implementation. The study indicated that rather moderate cable-tension capability provided satisfactory control and that tensions larger in magnitude than thruster capability are to be avoided.

REFERENCES

1. Willman, J.: "Lunar Docking Simulation Study." North American Aviation Report, NA63H-82. February 1963.

2. Hackler, C., Guthrie, G., and Moore, T.: "Preliminary Study of the Pilot Controlled LEM Docking Maneuver." NASA Project Apollo Working Paper No. 1075.

3. Lins, T., et al: "A Simulation Study of the LEM Docking Maneuver Using a Minimum Impulse Control Mode." NASA Project Apollo Working Paper No. 1082.

4. Russo, J.: Grumman Aircraft Engineering Corporation Presimulation Report No. LTP 570-2, March 4, 1963.

Docking Method	Attitude Control*	Max. Cable Tension (Lbs)	Displace. Error		Velocity (in/sec)				Attitude Error (Deg)				Translational & Attitude Fuel (Lbs)					
					Long.		Lat.		ϕ		ρ		Translational (CM)		Attitude (SIVB)		Attitude (C/SM)	
			Ave	σ	Ave	σ	Ave	σ	Ave		Ave	σ	Ave	σ	Ave	σ	Ave	σ
Direct Trans-Position	RCAH	---	.6	.394	.688	.322	.125	.125	.48	.05	.39	.089	5.48	.894	.265	.115	4.75	.316
	RC	---	.4	.4	.75	--	0	--	1.42	--	1.1	--	--	--	.34	--	5.72	--
	OL	---	1.4	--	1.25	.752	.25	--	1.7	--	.7	.39	6.66	1.3	.15	.02	2.62	.52
Tethered Trans-Position	RCAH	1	.2	--	1.5	--	.6	--	.76	--	2.0	--	2.64	--	.35	--	2.53	--
		5	.6	.071	1.38	.276	.375	.124	.415	.234	.833	.411	5.2	.45	.392	.098	4.44	.89
		10	.56	.214	1.3	.368	.52	.31	.74	.53	.68	.31	5.19	1.48	.298	.054	7.9	1.38
		20	.49	.36	1.9	.3	.361	.336	1.03	.755	.778	.257	7.53	1.95	.4	.114	6.84	3.44
		100	.445	.456	1.56	.542	.61	.105	.70	.541	1.06	.473	6.93	1.94	.526	.19	5.2	1.48
	RC	100	.6	--	2.0	--	1.5	--	1.76	--	1.9	--	5.62	--	.35	--	3.21	--
	OL	10	2.7	2.5	1.62	1.27	1.35	--	1.53	.831	3.9	2.1	5.13	1.4	.69	.07	6.08	.283
		100	2.27	.52	2.07	.735	1.66	.822	1.82	1.15	2.33	1.04	7.78	2.22	.868	.371	4.78	1.61

* RCAH - Rate Command-Attitude Hold
RC - Rate Command
OL - Open Loop

Table 1 - Average Transposition Docking Contact Conditions

Docking Method	Attitude Control*	Max. Cable Tension (Lbs)	Displace. Error		Velocity (in/sec)				Attitude Error (Deg)				Translational & Attitude Fuel (Lbs)					
					Long.		Lat.		ϕ		ρ		Translational (LEM)		Attitude (LEM)		Attitude (C/SM)	
			Ave	σ	Ave	σ	Ave	σ	Ave	σ	Ave	σ	Ave	σ	Ave	σ	Ave	σ
Direct Lunar Orbit	RCAH	---	.9	.576	.675	.434	1.05	.826	1.03	.754	1.0	.46	1.85	.71	.494	.13	.301	.305
	OL	---	1.88	1.29	1.5	.806	2.49	1.92	3.85	7.8	5.25	7.9	1.8	.632	3.53	2.06	.204	.103
Tethered Lunar Orbit	RCAH	1	.36	.71	1.05	.4	.942	.44	.84	.543	.678	.37	1.21	.15	.51	.118	.334	.11
		10	.725	.442	2.5	.54	1.11	.54	.686	.26	1.33	.533	2.3	.794	.953	.214	.391	.11
		100	.3	--	3.0	--	1.8	--	1.31	--	1.2	--	1.56	--	.62	--	.49	--
		250	.778	.21	1.75	.742	2.74	.97	.981	.296	.89	.505	14.7	6.08	1.38	.464	.839	.572
	OL	1	3.06	1.73	1.67	.46	2.63	1.0	2.36	.57	4.62	1.5	2.08	.55	5.34	1.1	.5	.17
		10	3.29	1.92	2.15	.92	1.48	.75	3.87	2.7	5.19	1.4	2.89	1.6	4.9	1.0	1.01	.57
		250	3.8	--	8.5	--	12.1	--	5.1	--	9.0	25.5	--	--	12.4	--	10.4	--

* RCAH - Rate Command-Attitude Hold
OL - Open Loop

Table 2 - Average Lunar Orbit Docking Contact Conditions

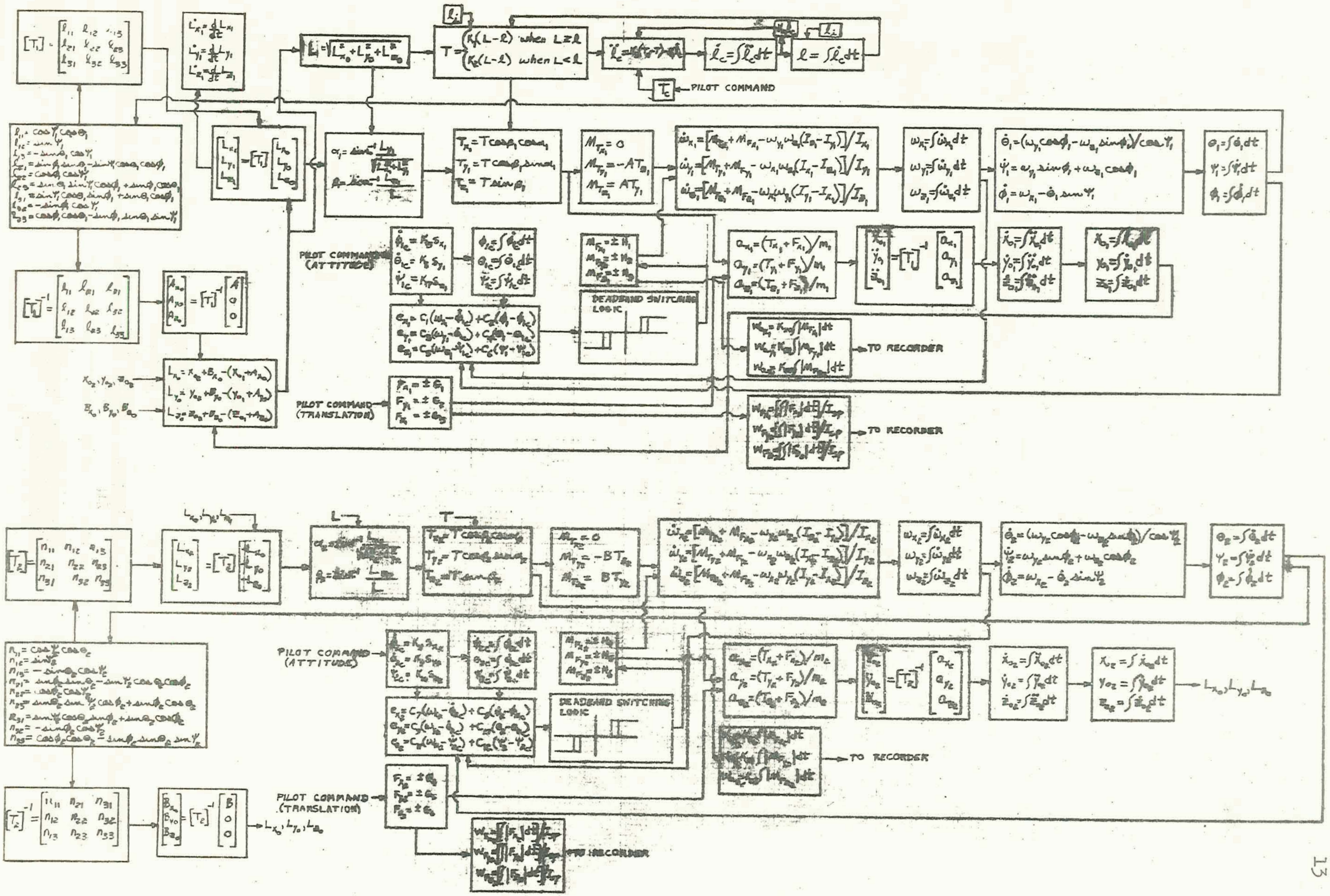

Figure 1.- Tethered docking simulation

NASA
S-63-18311

Figure 2.- Simulator cockpit

2245-64

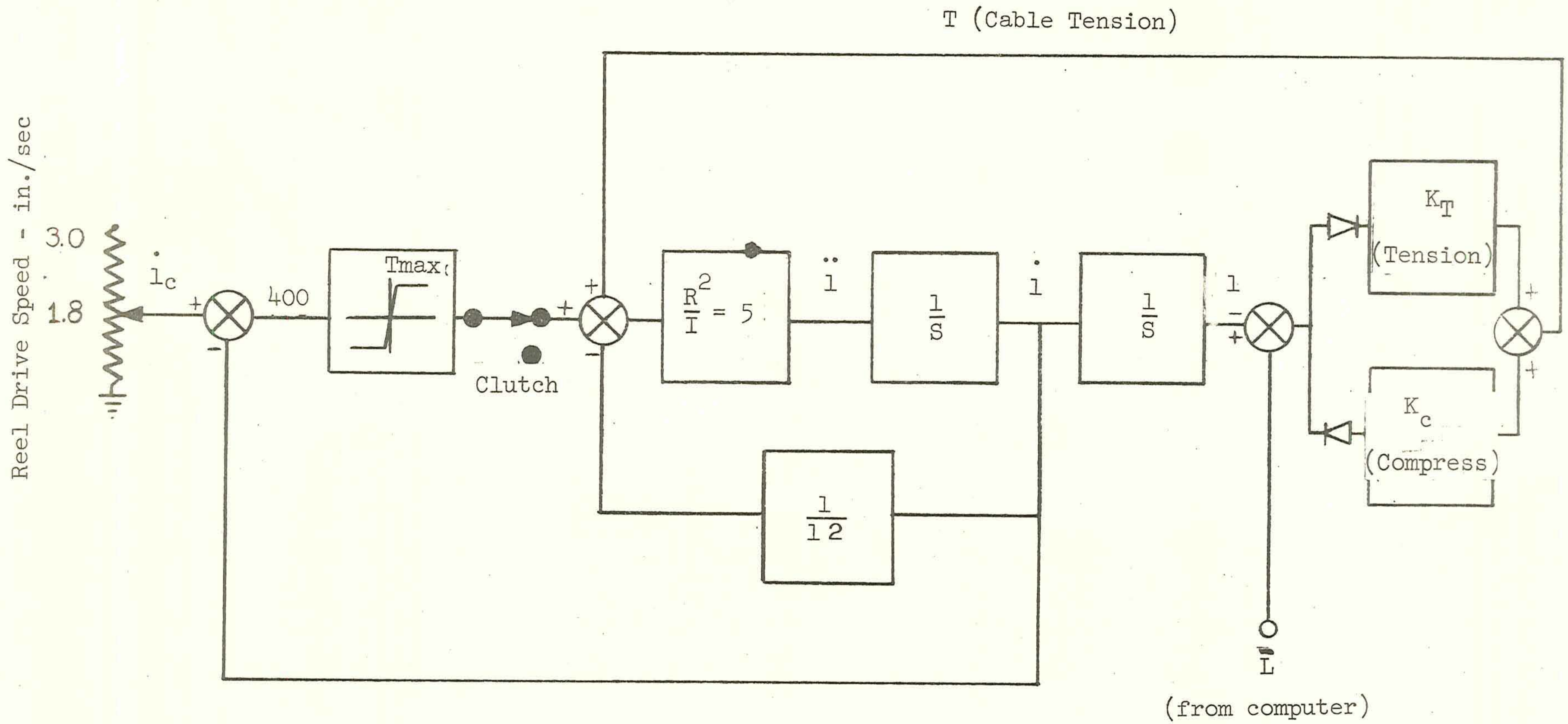

Figure 3.- Reel control